

**Summary of Research for NASA Grant NAG5-13206**  
**“Radial Velocity Detection of Extra-Solar Planetary Systems”**  
**1 June 2003 to 31 May 2004**  
**McDonald Observatory, The University of Texas**  
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This NASA Origins Program grant supported four closely related research programs at The University of Texas at Austin: 1) The McDonald Observatory Planetary Search (MOPS) Program, using the McDonald Observatory 2.7m Harlan Smith telescope and its 2dcoudé spectrometer, 2) A high-precision radial-velocity survey of Hyades dwarfs, using the Keck telescope and its HIRES spectrograph, 3) A program at McDonald Observatory to obtain spectra of the parent stars of planetary systems at  $R = 210,000$ , and 4) the start of high precision radial velocity surveys using the Hobby-Eberly Telescope. The most important results from NASA support of these research programs are described below. A list of all papers published under support of this grant is included at the end.

### **The 2.7m McDonald Observatory Planetary Search (MOPS)**

During this grant, we started de-emphasizing the 2.7m program, as this instrument is capable of achieving only about  $6\text{--}8\text{ ms}^{-1}$  radial velocity precision, and the observations are quite labor intensive. We are now requesting 6 observing runs per year with the 2.7m 2dcoudé spectrograph of 3-4 nights each. We are targeting this program to the specific niches where it can still make a significant contribution. The 2.7m MOPS target list now includes about 270 stars.

### **A brown-dwarf companion to HD 137510.**

Since the beginning of precise Doppler surveys, one surprising enigma has emerged: the relative paucity of spectroscopic binaries where the secondary mass lies in between the stellar and planetary mass regime. This gap in the mass function for close-in ( $a \lesssim 4\text{ AU}$ ) companions to solar-type stars is often referred to as the “Brown Dwarf Desert”. Our 2.7m radial velocity survey has detected a companion to HD 137510 (G0IV), with a minimum mass of  $26\text{ M}_{Jup}$ . This brown dwarf companion to HD 137510 was also independently and simultaneously found by the Thüringer Landessternwarte Tautenburg (TLS) planet search program. HD 137510 (= HR 5740 = HIP 75535) is a bright ( $V = 6.3$ ) G-type star at a distance of  $41.75 \pm 1.7\text{ pc}$ . We performed a model atmosphere analysis of a high resolution, high SNR spectrum of HD 137510. We find that the star has a mass of  $M = 1.3 \pm 0.1\text{ M}_{\odot}$ , an effective temperature  $T_{\text{eff}} = 5896 \pm 57\text{ K}$ , a  $\log g$  of  $4.0 \pm 0.1$ , a radius  $R$  of  $1.9 \pm 0.2\text{ R}_{\odot}$ , an age of  $3.4 \pm 0.8\text{ Gyrs}$ , and  $[\text{Fe}/\text{H}] = 0.16 \pm 0.07\text{ dex}$ . The object is thus metal rich compared to the Sun. It thus appears that HD 137510 was a metal rich late F-type star which has now started its evolution away from the main sequence. Interestingly, Smith *et al.* (2001) noted that HD 137510 possibly underwent chemically fractionated accretion and represents a good candidate for having a close-in giant planetary companion. The combined McDonald and TLS data sets are best fit with an orbital period of  $798.2 \pm 1.4\text{ days}$ , a  $K$  velocity of  $531.6 \pm 5.3\text{ m s}^{-1}$ , and an eccentricity of  $0.402 \pm 0.008$ . The resulting mass function of this binary yields a minimum mass for the companion of  $26 \pm 1.4\text{ M}_{Jup}$ , and the semi-major axis is  $1.85 \pm 0.05\text{ AU}$ . These results were published in Endl *et al.* (2004).

## A High-Precision Radial Velocity Survey of Hyades Dwarfs

From 1996 through 2003 we used the Keck 1 telescope with its HIRES spectrograph to conduct high precision radial velocity observations of a sample of 98 Hyades dwarf stars. The overall goals and methodology of the program are given by Cochran *et al.* 2002. The basic motivation for this program was that the Hyades represent a sample of stars of the same age and overall metallicity. This sample allows us to use an extremely homogeneous sample of stars to explore the dependence of the process of planet formation on only a single independent variable: the stellar mass.

During the time covered by this grant, we have completed this survey, and we concentrated on publishing all of the final results. A few stars that are showing radial velocity variations that do not appear to be related to stellar activity are being monitored with the HET and VLT, and simultaneous photometry of these stars is being obtained with either the ROTSE automated photometric telescope. The HET is the ideal facility to use for this type of synoptic radial velocity monitoring.

We presented a summary of the Hyades planet search results in Paulson *et al.* (2004). In that papers, we also discussed the effects of stellar activity on radial velocity measurements. The level of radial velocity scatter due to rotational modulation of stellar surface features for the Hyades was in agreement with the predictions of Saar and Donahue (1997) - the maximum radial velocity rms was up to  $\sim 50 \text{ m s}^{-1}$ , with an average rms of  $\sim 16 \text{ m s}^{-1}$ . In this sample of 94 stars, we found one new binary stellar system, two stars with linear trends indicative of binary companions, and no close-in giant planets. We discussed the limits on extrasolar planet detection in the Hyades and the constraints imposed on radial velocity surveys of young stars.

We have conducted a differential abundance analysis of our Hyades F-K dwarfs to search for evidence of stellar enrichment from accreted hydrogen deficient disk material (Paulson *et al.* 2003). We derived a cluster mean  $[\text{Fe}/\text{H}] = 0.13 \pm 0.01$ . Two stars showed abundances  $\sim 0.2$  dex larger than the cluster mean. Additionally, one star, which was added by a recent study as a cluster member, showed significantly lower abundances than the cluster mean. These three stars had questionable membership characteristics. The remaining stars in the survey had an rms of 0.04 dex in the differential  $[\text{Fe}/\text{H}]$  values. The Hyades cluster members have apparently not been significantly chemically enriched. The abundance ratios of Si, Ti, Na, Mg, Ca and Zn with respect to Fe are in their solar proportions.

## Hobby-Eberly Telescope Programs

### HET HRS radial velocity precision.

During the course of this grant, we have conclusively demonstrated the truly outstanding radial velocity precision obtained with the High Resolution Spectrograph of the Hobby Eberly Telescope. So far, we have observed 173 F-M dwarfs four or more times. The time span of the data for each star ranges between one week and over three years. Of these, 20 stars show large-amplitude variations indicative of binaries, and 11 additional stars show rms variations greater than  $20 \text{ m s}^{-1}$ , but probably not large enough to be due to binary stellar companions. These stars represent good candidates for short-period planetary companions. Of the remaining 142 stars, if we examine just the 112 stars with rms of  $8 \text{ m s}^{-1}$  or less (the bulk of the sample), then both the mean and the median rms of these remaining “stable” stars is just  $3.6 \text{ m s}^{-1}$ . This clearly demonstrates that we have already achieved routine radial velocity precision of  $3 \text{ m s}^{-1}$  with the HET-HRS in routine “production mode” on a large sample of a wide variety of stars over a substantial time period. Indeed, a significant fraction of our stars are showing radial velocity precision of  $2 \text{ m s}^{-1}$  or better, which is comparable to the precision achieved for high SNR observations with the ESO VLT/UVES by Kürster *et al.* 2003.

### A planetary companion to HD 37605.

During this grant period, we discovered a planetary-mass companion to HD 37605, one of the stars on our HET planet survey. HD 37605, a  $V = 8.69$  K0 dwarf, is quite typical of the stars in our HET program list. Our typical HET observing methodology is to obtain about 4-5 radial velocity measurements over the course of 1-2 weeks, in order to search for short-period “hot-Jupiter” RV variability. If a star appears stable on short timescales, it is then scheduled for less frequent observations in order to search for longer period orbits. The initial set of observations of HD 37605 were constant to within the observational error, but the next observation taken about one month later showed a decrease of about  $200 \text{ m s}^{-1}$ . This star was then put back into the queue at high priority for frequent observations. The HET then obtained spectra every 3-4 days during the decrease in radial velocity. We were easily able to fit a new orbital solution as the data became available from each night of HET observations. It quickly became obvious that the radial velocity minimum and periastron passage would occur just as the star was being lost from the HET observability window; the last HET data points would be obtained during twilight. It was critical to attempt to obtain nightly HET velocity measurements during this crucial orbital phase. The queue-scheduled operation of the HET enabled the crucial data to be obtained.

HD 37605 has a planetary-mass companion in a highly eccentric orbit. We obtain a period of  $54.2 \pm 0.2$  days, eccentricity of  $0.737 \pm 0.010$ , and a K velocity of  $262 \pm 5 \text{ m s}^{-1}$ . This gives a minimum companion mass of 2.84 Jupiter masses, and an orbital semi-major axis of 0.26 AU. The periastron distance of 0.0686 AU is large enough that we would not necessarily expect the orbit to be circularized in the age of the primary star. The rms residual of the HET/HRS data from the orbital solution is  $4.4 \text{ m s}^{-1}$ . From our radial velocity template spectrum (taken without the  $I_2$  cell), we derive an iron abundance of the primary star of  $[\text{Fe}/\text{H}] = 0.37$ , which makes HD 37605 a super-metal-rich star.

These observations of HD 37605 clearly demonstrate the power of the HET for this type of radial velocity survey. The telescope aperture and system sensitivity allow us to obtain excellent quality data on this  $V=8.7$  star. The queue scheduled operation of the telescope permits us to change our program priorities dynamically, and to obtain the data on critical targets *when the observations are most needed*. We did not need to wait until our next regularly scheduled observing run to obtain the necessary follow-up data. We simply reallocated our “Priority 1” observing time so that the HD 37605 observations would be at the top of the telescope queue. We communicated the importance of these observations to the HET operations staff, and they responded to accommodate our needs.

### A Neptune-mass inner planet in the $\rho^1$ Cancri System

We have discovered a 4<sup>th</sup> planet in the  $\rho^1$  Cancri system. This newly discovered planet is in an orbit with a period of just 2.8 days. This planet is the lowest mass extra-solar planet yet found around a Sun-like star - a planet with an  $m \sin i$  of only  $14.21 \pm 2.91$  Earth masses! High precision radial velocity measurements taken from late 2003-2004 at McDonald Observatory with the Hobby-Eberly Telescope revealed this inner planet at 0.04 AU.

$\rho^1$  Cancri already had three known planetary-mass companions, with orbital periods of 14d, 44d, and 5360d. We worked with Barbara McArthur and Fritz Benedict, who were combining Hubble Space Telescope Fine Guidance Sensor astrometric data with all available ground-based radial velocity data on this system to attempt to determine the orbital inclination (and hence the mass) of the outer planet in the system. As part of this effort, we used the HET to obtain an intense set of high precision radial velocity observations of the star, in order to provide tighter constraints on the orbits of the two known inner planets, knowing these that observations would also be able to uncover any additional planetary companions with K velocities greater than  $4 \text{ m s}^{-1}$

and orbital period of a year or less. By taking advantage of the queue-scheduled operation of the HET, we recorded well over 100 radial velocity measurements in a span of about 190 days. Analysis of the residuals of the HET data, after removal of our best overall fit to the orbits of the three known gas-giant planets to all of the radial velocity and astrometric data, revealed a period of 2.81 days. A simultaneous 4-planet model to the data revealed an object in a low eccentricity orbit with a period of 2.81 days. The velocity K amplitude of this orbit is only  $6.7 \text{ m s}^{-1}$ , which is above the expected internal radial velocity “jitter” variability for this star. The 2.81 day radial velocity signal is coherent over the entire time-span of the HET data, which would not be expected for stochastically excited internal stellar sources. In retrospect, the clear signal of this 2.81 day orbital period planet can also be seen in Figure 9 of Marcy *et al.* (2002), which shows the periodogram of the residuals of their Lick data. This gives strong independent confirmation that this radial velocity periodicity is intrinsic to the  $\rho^1$  Cancri system, and is not an artifact of the observation or data analysis techniques used on either the HET or Lick data. The 2.81 day periodic signal has a false-alarm probability of  $1.7 \times 10^{-9}$  in the HET data and  $1.1 \times 10^{-6}$  in the Lick data, giving further strong evidence for its reality. We interpret this 2.81 day radial velocity periodicity as the stellar reflex motion due to an extremely low mass planet in orbit around the star. The mass function from the radial velocity solution, combined with our assumed stellar mass of 0.95 solar masses, gives an  $m \sin i$  of this innermost 2.8 day planet of  $0.047 \pm 0.01 \text{ M}_J$ . If we assume that all of the planets in the  $\rho^1$  Cancri system are coplanar and adopt the  $53^\circ$  inclination of the outermost planet found from our analysis of the HST astrometric data, then we compute a true mass for this innermost planet of about 17.7 Earth masses, close to the mass of Neptune. This fourth planet,  $\rho^1$  Cancri e, is the lowest mass extrasolar planet yet found around a solar-type star.

### Papers Published Under This Grant

1. “Searching for Planets in the Hyades V: Activity Induced Radial Velocity Jitter” (D. B. Paulson, W. D. Cochran, and A. P. Hatzes) *Astron. J.* **127** 3579-3586, 2004.
2. “HD 137510: An Oasis in the Brown Dwarf Desert” (M. Endl, A. P. Hatzes, W. D. Cochran, B. McArthur, C. A. Prieto, E. Guenther, A. Bedalov, and D. B. Paulson), *Astrophys. J.* **611** 1121-1124, 2004.
3. “The First HET Planet: A Companion to HD 37605” (W. D. Cochran, M. Endl, B. McArthur, D. B. Paulson, V. V. Smith, P. J. MacQueen, R. G. Tull, J. Good, J. Booth, M. Shetrone, B. Roman, S. Odewahn, F. Deglman, M. Graver, M. Soukup, M. L. Villarrreal Jr) *Astrophys. J. (Letters)* **611** L133-L136, 2004.
4. “Detection of a Neptune-mass planet in the  $\rho^1$  Cancri system using the Hobby-Eberly Telescope” (B. E. McArthur, M. Endl, W. D. Cochran *et al.*) *Astrophys. J. (Letters)*, in press, 2004.
5. “Low-mass companions to Hyades stars” (E. W. Guenther, D. B. Paulson, W. D. Cochran and A. Hatzes) *Astron. Astrophys.*, submitted, 2004.